Estimation of 80 kW Solar Generating Station in Kabudrahang Iran: A Comparative Study

R. Kazemi Golkhandan¹, H. Torkaman², A. Keyhani³

¹ Faculty of Electrical & Computer Engineering, University of Birjand, Birjand, Iran. Email: reza.kazemi@birjand.ac.ir, Cellphone: (+98915) 3053805
² Faculty of Electrical Engineering, Shahid Beheshti University, A.C., Tehran, Iran. Email: H_torkaman@sbu.ac.ir, Phone: (+9821) 73932525, Cellphone: (+98912) 7993389
³ Department of Electrical and Computer Engineering, Ohio State University, Ohio, USA. Email: keyhani1@osu.edu, Phone: (++1614) 292-2572.

Abstract: Estimation of solar energy generation in the integrated power systems must be performed for power system the long-term planning and the short-term control. Irradiation is one of the main factors affecting the out coming energy of solar system. Hence, investigation of solar irradiation on the horizontal surface helps in proper and efficient implementation of solar energy system. Capturing much more energy from the irradiation, by the Photovoltaic (PV) cells, results in enhancement of out coming energy of PV station. This paper is going to study the impact of implementation two topologies for energy harvesting in PV stations. The topologies are as follows: (a) PV station with multilevel boost converters and inverters, (b) PV station with only multilevel inverters. Studies have been performed on 80 KW PV test station, located in Kabudrahang, Iran. The comparison between the results demonstrates much more solar energy harvesting in the case of applying multilevel converters in the output of PV arrays. Simulation results show the promising result of the proposed topology in harvesting maximum power from a PV station.

Keywords: Solar Generating Station, Boost Converter, Inverter, Maximum Power Point, Photovoltaic model.

1. Introduction

The increase in the worldwide installed PV capacity, the concept of Maximum Power Point (MPP) tracking has been developed in PV systems [1]. MPP tracking is an essential component
of PV systems. This scheme ensures that the system can always harvest maximum power generated by the PV system independent of change in environmental conditions, namely ambient temperature and solar insolation \[2\]. Several MPP tracking techniques together with their implementation are reported in the references \[3\], \[4\]. Since the power–voltage (\(P–V\)) characteristic curve varies non-linearly with solar irradiation and atmospheric temperature conditions, tracking MPP is a challenge and has been successfully achieved, using several methods \[5\], \[6\].

For calculation of a PV station output power, knowing the environmental parameters, irradiation, and the temperature is of particular importance \[7\], \[8\]. As irradiation and temperature variations during the day, they must be studied as functions of time. Irradiation on a particular day depends on the angle that sun makes with the PV panels, the air mass and the cloud cover \[9\]. In \[10\], Prediction of daily global solar irradiation is performed applying temporal Gaussian process regression. In \[11\], a methodology is proposed to choose a representative daily-duration irradiance signal from long-term irradiance data.

In the case of unavailable data of irradiation, approaches have been exploited to estimate the irradiation, from a single PV module output parameters. Authors of \[12\] propose a closed-form analytical estimator of the irradiation based on measurements of the DC voltage, current, and cell temperature and a model of PV arrays. Similarly, Authors of \[13\] propose a globally convergent estimator based on the immersion and invariance (I&I) principle. In \[14\], solar irradiation forecasting is performed applying artificial neural network and random forest methods. In \[15\], temperature and DC electrical measurements are used to perform real-time estimation of the irradiation. The method has the drawback of requiring the PV system to move in three different states (panel underload, short circuit or open circuit), a feature that is not typically implemented in commercial PV systems. Therefore, it must be noted that the knowledge of irradiation and temperature plays an essential role in the output parameters investigation of PV systems. In \[16\], estimation and validation of daily global solar irradiation by day of the year-based models is investigated for different climates. Besides, validity and effectiveness of the ensemble technologies and hybrid methods is concluded. Authors of \[17\], develop a novel estimation approach for the monthly average daily solar radiation with its complex spatial pattern via machine learning techniques.
A PV station consists of PV modules, in which a number of PV cells are connected in series. A number of PV modules connected in series form a string and a number of strings connected in parallel form arrays. Series and parallel connections enhance the voltage and current ratings of the PV system, accordingly [18].

As irradiation and temperature determine the output voltage of PV arrays, these factors make PV systems intermittent, unpredictable and unreliable [19]. Irradiation, directly affects the output voltage of a PV cell and temperature inversely affects the output voltage. As irradiation goes up and temperature goes down in the allowable range, the output voltage of PV cell increases, and vice versa.

Power electronic converters, applied in the PV stations, are capable of operating upon a certain level of voltage. This fact limits the harvested output power of PV systems during operation in the case of low irradiation and high temperature. In these conditions, the power electronic inverter in the PV system would not be capable of converting DC to AC power in the required level of voltage. With the implementation of high ratio DC-DC converters, MPPT and voltage regulation would be achieved, despite variations in irradiation and temperature [20], [21]. This way results in the efficiency improvement of the PV system. In [22], a MPP tracking algorithm based on Monod equation, applied to estimate the power output for each current output of the PV station, is proposed to estimate the required duty cycle for the converter of the PV system.

In this paper, initially, a model of the PV module has been extracted. Then, two cases of a typical PV station with the capacity of 80 KW in Kabudrahang, Iran have been explained and studied in detail. One case is related to the time when PV arrays are directly connected to the power grid through multilevel inverters. The inverter is used in the PV station to change the DC output voltage of PV arrays to the grid AC voltage level. The other case is related to the time when multilevel boost converters and inverters are applied in the PV station. Applying boost converter to increase the output voltage level of PV cells facilitates to reach the cut-off voltage of the inverter. More power harvested during operation of PV station with proper coordination of converters and PV station voltage output. Input data of irradiation and temperature profiles in the location of PV station have been gathered from practical measurements. Simulations have been performed to study the effectiveness of the proposed strategy on the 80 kW PV station.
2. Model of PV Module

To design a PV station, first of all a PV source model must be extracted. Here, for the studies, a single diode model of PV module with series and parallel resistances has been considered. It is depicted in Fig. 1 [7].

It consists of a current source, a diode, and series and parallel resistances. The voltage-current (V–I) relationship of PV can be written from Kirchhoff’s current law [23] as (1).

\[ I = I_{ph} - I_o \left( \exp \left( \frac{V + R_s I}{n_s V_t} \right) - 1 \right) - \frac{V + R_s I}{R_p} \]  

(1)

Where \( V \), is the module output voltage and \( I \) is the output current. \( I_{ph} \) and \( I_o \) are the photogenerated current and the dark saturation current, respectively. \( V_t \) is the junction thermal voltage. \( R_s \) and \( R_p \) are the series and parallel resistances, respectively. \( n_s \) is the number of series-connected cells in the module. \( V_t \), thermal voltage of a diode, is expressed by (2).

\[ V_t = \frac{KTA}{q} \]  

(2)

Where \( K \) is Boltzmann’s constant, \( T \) is the junction temperature in Kelvin, \( A \) is the diode ideality factor, and \( q \) is the electronic charge. The model presented in Fig. 1 has five unknown parameters based on the (1): \( I_{ph} \), \( I_o \), \( V_t \), \( R_s \), and \( R_p \). The manufacturer’s datasheet provides the following information about the module: \( I_{sc} \), \( V_{oc} \), \( V_{mpp} \), \( I_{mpp} \) which stand for short circuit current, open circuit voltage, the voltage at MPP and current on MPP accordingly. Also, the temperature coefficient for short-circuit current \( K_i \), and open-circuit-voltage \( K_v \) are determined in the datasheets. The PV modeling objective is to estimate the model parameters under standard test conditions (STC), and also under varying environmental conditions from datasheet information provided by the manufacturer of the module. The parameter estimation is based on the numerical method such as Gauss-Seidel. \( (0, I_{sc})\), \( (V_{mpp}, I_{mpp})\), \( (V_{oc}, 0)\) is the specified points on the (V-I) curve which help in estimation of the parameters. In [24], parameter estimation of PV cells by applying some selected evolutionary algorithms with the use of datasheet information at three major points of I-V characteristic is performed. Authors in [25]
propose maximum likelihood estimator (MLE) and Newton Raphson (NR) resolution for identifying unknown parameters of single diode PV module at different test conditions. Here, to simplify (1), the term "-1" is neglected in comparison with the exponential term for convenience. Equations (3) to (5) are obtained by substituting the values of remarkable points in (1).

\[ I_{sc} = I_{ph} - I_o \left( \exp \left( \frac{R_s I_{sc}}{n_s V_t} \right) \right) - \frac{R_s I_{sc}}{R_p} \]  

\[ I_{mpp} = I_{ph} - I_o \left( \exp \left( \frac{V_{mpp} + R_s I_{mpp}}{n_s V_t} \right) \right) - \frac{V_{mpp} + R_s I_{mpp}}{R_p} \]  

\[ 0 = I_{ph} - I_o \left( \exp \left( \frac{V_{oc}}{n_s V_t} \right) \right) - \frac{V_{oc}}{R_p} \]  

In order to estimate five unknown parameters, in addition to the aforementioned equations, (3) to (5), two other equations are needed. First, as the derivative of PV output power with respect to PV voltage is zero at MPP, (6) can be applied as one equation for unknown parameter estimations.

\[ \frac{dP}{dv}(V = V_{mpp}, I = I_{mpp}) = 0 \]  

Second, the slope of V-I characteristic at short-circuit point, which is calculated applying (7) [26], can be applied as another equation for unknown parameter estimations.

\[ \frac{dI}{dv}(V = 0, I = I_{sc}) = -\frac{1}{R_{sh0}} \]  

For the studies conducted in this paper, Mitsubishi Electric, PV-MF165EB3, is used as test PV module. Table 1 illustrates the provided values on the module datasheet followed by the values of the unknown parameters estimated by the Gauss-Seidel method [7].

3. PV Station with Boost Converter and Inverter

To harvest maximum available power from a PV station, a boost converter is applied to the system to step up the output voltage of the PV arrays in the cases of low irradiation and high temperature. This approach helps in increasing the value of output voltage to the values above the cut-off voltage of the inverter. Hence, the inverter starts operating in these moments that
were not able to operate when PV station was equipped only with the inverter. The output voltage of a boost converter in the PV system is calculated by (8) [27], [28].

$$V_{dc} = \frac{V_{pv}}{1-D}$$  \hspace{1cm} (8)

where $D$ is duty ratio of the power electronic switch in the converter. Equation (8) is based on the continuous mode of conductance. Hence, the current of the inductor in the converter would not be zero during operation. As mentioned in [26], the limit for the continuous mode of converter conduction can be written as (9) [29].

$$I_{pv} = \frac{\Delta I_L}{2}$$  \hspace{1cm} (9)

where $I_{pv}$ and $\Delta I_L$ refer to the average value of inductor current, applied from the output of the PV arrays and its peak to peak variation, accordingly. Equation (10) demonstrates how the value of peak to peak voltage variation is calculated in the boost converter [27].

$$\Delta I_L = \frac{V_{pv} \cdot D}{f \cdot L}$$  \hspace{1cm} (10)

By substituting the value of $\Delta I_L$ in (10), from (9), the duty ratio can be calculated by (11).

$$D = \frac{2 I_{pv} \cdot L_{min} \cdot f_s}{V_{pv}}$$  \hspace{1cm} (11)

Where $L_{min}$ represents the minimum value of the inductance that ensures continuous mode of operation.

As illustrated in (11), duty ratio depends on the values of PV arrays voltage and current, the inductance of the converter and switching frequency. The value of duty ratio is limited by the parameters mentioned here. Hence, according to (11), for a limited value of duty ratio, the output voltage of the converter would be limited too. In this condition, the output voltage of the converter would not be sufficient to be applied to the inverter. Finally, the PV system can't provide power to the grid because of the insufficient output voltage of the converter, and it limits the output power of the PV system during low irradiation and high-temperature conditions.

To overcome this problem, converters with lower step-up voltages can be proposed to harvest power at lower voltage levels. Therefore, the overall efficiency of the system would be increased.
3.1 PV Station with Inverter

When PV arrays are directly connected to the inverter, the PV arrays output voltage must be above a cut-off value for initialization of inverter operation. In this condition, space vector modulation is applied to produce the output voltage of the inverter. The output voltage of the inverter is related to its input voltage, applied from PV arrays, by the modulation index. This index varies between zero and one. The output line to line voltage of inverter can be calculated applying (12) [27].

$$V_{i_{L-L}} = \frac{V_{dc}}{\sqrt{2}}M_a$$ (12)

The grid voltage determines the output voltage of the inverter that is maintained by the grid, it must be regarded as constant. Therefore, during variations in the output voltage of PV arrays, modulation index variation helps in achieving a constant voltage in the output of the inverter. The minimum value of PV arrays voltage can be calculated, considering $M_a = 1$. So the minimum value of DC voltage can be calculated applying (13).

$$V_{dc, min} = \sqrt{2}V_{i_{L-L}}$$ (13)

Like the previous section, during a day when the output voltage of PV arrays falls below a certain level, named as cut-off voltage, the inverter would not operate. Therefore, to harvest maximum power in the output, the PV arrays must be connected to an inverter with a lower cut-off voltage.

3.2 Formulation of Irradiation on the PV Arrays

For all of the calculations, the irradiation on the PV panels must be calculated. Equation (14) illustrates how the irradiation on a horizontal surface is calculated [30].

$$I_{hor} = S . E_o . [\cos \delta . \cos(\varphi - \beta) \cos \omega + \sin \delta . \sin(\varphi - \beta)]$$ (14)

S, solar constant, is defined as rate of energy received by a unit area perpendicular to the rays at a distance of one astronomical unit. The value of solar constant is $1367 W . m^{-2}$ [31]. $E_o$, eccentricity correction factor of the earth’s orbit, is calculated applying (15) for each day of year [32].

$$E_o = 1 + 0.033 \cos \left( \frac{2\pi d_n}{365} \right)$$ (15)
Where \( d_n \) is the day number of the year.

\[ \delta, \quad \text{declination angle}, \quad \text{is calculated applying (16). Equation (16) is an empirical formula [33].} \]

\[ \delta = 23.45 \sin \left( \frac{360( d_n + 284)}{365} \right) \]  

(16)

\( \varphi \) is the latitude of the location, \( \omega \) is the solar hour angle, and \( \beta \) is tilt angle. Detection of the optimum value of tilt angle is studied in [34].

Equation (14) is used to calculate the irradiation on a surface outside the earth's atmosphere. A fraction of this irradiation reaches the surface of the earth, due to diffusion of the rays and their absorption into the atmosphere.

### 4. Case Study Statement

In this paper, for the studies, A 80 kW PV station has been considered as the test system. As explained before, each solar PV arrays is a combination of some modules first connected in series to achieve the desired voltage and then connected in parallel to allow the system to produce the desired current.

The values of the photo-generated and dark saturation current in the module and string are the same, but the series and parallel resistances are different and must be calculated. For the 80 kW arrays consisting of PV-MF165EB3 modules of Table. 1, with 15 modules per string and 32 strings in parallel, the estimated parameters are extracted as the demonstrated data in Table. 2.

\( n_p \) is the number of modules connected in parallel in an array.

Both of the topologies, PV arrays directly connected to the inverter and PV arrays connected to the inverter through DC-DC boost converter have been implemented on the considered test system and the results are demonstrated in next part. There have been applied multilevel inverters in the proposed topology. As mentioned previously, irradiation and temperature at the location of the PV arrays determine the output voltage level of the PV arrays. When the irradiation level is high and the temperature is low, converters with higher voltage levels are used. Conversely, when the irradiation level is low and the temperature is high, converters with lower voltage levels are used. Fig. 2 (b) demonstrates topology two, when the PV arrays are connected to the inverter through DC/DC boost converter. The advantage of this topology is the boost converter that provides a stable and high voltage for the inverter. Therefore, the inverter is
rated at a lower current rating for the same power level. There have been applied multilevel converters in the proposed topology. This would result in much more energy harvesting during working conditions because when the voltage of the PV arrays is not sufficient for the inverter to operate, a boost converter is used to step up the PV arrays voltage to a value that is above lower cut-off voltage for the inverter.

The demonstrated topology in Fig. 2 (a) has the benefit of lower cost because the cost of the boost converter is not considered. The advantage of the second topology in Fig. 2 (b) is the boost converter provides a stable and high voltage for the inverter.

In both topologies, the output line to line voltage of the inverter has a square shape. To omit the harmonics and extract a sinusoidal AC voltage, suitable to be injected to the power grid, LC filters are applied in the point of connection of the inverters to the power grid. Application of delta-wye connection of the transformer helps in trapping the third harmonic of voltage and also providing the null point for the network.

The value of the parameters like voltage, current, and power in the output of a PV system depends on temperature and irradiation at the location of the PV arrays. To investigate how these parameters’ values change by temperature and irradiation, a sample day of a year, here 5\textsuperscript{th} of October at 10:10 am, has been regarded and the investigations are performed. Figs. 3 (a) to (d) demonstrate how voltage- current- output power, in the case of applying two topologies, change by temperature and irradiation variations.

Fig. 3 (a) demonstrates that in the case of increasing the irradiation, in a fixed temperature, the PV arrays output voltage increase. In a fixed level of irradiation, by increasing temperature, the value of PV arrays output voltage decrease. In the case of study, the maximum value of the PV arrays output voltage is 448.92 V. Fig. 3 (b) demonstrates that increasing irradiation and decreasing temperature, result in increasing the level of out coming current. The maximum value of PV arrays out coming current is 160 A. Figs. 3 (c) and (d) demonstrate the output power of the PV station applying two mentioned topologies. It is evident that in the case of applying boost DC/DC converter in the output of PV arrays, the harvested energy increases. Boost converter helps in enhancing the output voltage level to the values higher than the cut-off voltage level of the inverter.
5. Simulation and Implementation Results and Analysis

Here, for the simulations, a period of one year has been considered. The simulation results are used to make a comparison between two topologies. Specific day in weeks, Wednesdays in this paper, have been regarded as sample days. Irradiation and temperature profiles at the location of PV station, Kabudrahang, have been extracted from practical measurements.

Irradiation at the location of the PV station during the year under study is given in Fig. 4. The maximum value of the energy from irradiation at the location of the station is 8.6 KWh per day. Fig. 5 illustrates temperature profile at the location of the PV station. Minimum and maximum values of the measured temperatures are -9.94 and 30.47, accordingly.

Latitude longitude coordinates for Kabudrahang are: 35.21°N and 48.72°E. Tilt angle is considered 30° [34]. Applying (15), (16), $E_0$ and $\delta$ are calculated for the Wednesdays of a year and the values are mentioned in Table. 3.

Irradiation, voltage and current profile of the mentioned PV system during sampling day hours of summer quarter are illustrated in Fig. 6 (a) to (c).

As depicted in Fig. 6 (a), irradiations on the PV arrays vary during times of the days. Maximum values of irradiation on the Wednesdays of summer quarter vary between 846.91 to 1038.6 watts per square meters. Maximum value, 1038.6 watts per square meters, occurs on 7th Wednesday of summer quarter. Minimum values of irradiation on the Wednesdays of summer quarter vary between 1 to 4.22 watts per square meters. Minimum values occur at the moments of sunrise and sunset. Here, minimum value, 1 watt per square meters, occurs on 5th Wednesday of summer quarter. Regarding the irradiation profile in the 13 weeks of the summer quarter, as depicted in Fig. 6 (a), the output voltage of the PV arrays can be calculated as Fig. 6 (b). The line to line voltage of power grid has been regarded 240 volts in the simulation. According (13), the minimum value of dc voltage in the input of the inverter must be 340 volts to initialize the inverter operation. As the output voltage of PV arrays in the summer quarter does not reach this value, the inverter would not start operating. Fig. 7 (a) demonstrates this fact. For energy harvesting, the boost converter is added to the PV station. In the case of applying a boost converter, its output voltage is preserved at 480 V DC, with a switching frequency of 5KHz and inductance of 5mH, while the inverter output voltage is preserved at 240 V AC. This would result in energy harvesting during the summer quarter as depicted in Fig. 7 (b).
To have a comparison between two cases, output power profiles of a PV system with only boost converter and PV system with boost converter and inverter is studied in Fig. 7.

To have a numerical comparison between two cases, the daily output energy of PV station with the inverter and output energy of PV station with boost converter and inverter, during 13 Wednesdays of summer quarter, have been calculated and mentioned in Table. 4. Application of boost converter in the output of PV arrays helps in increasing the output energy harvesting. The maximum value of the output energy is 228.2 KWh which is attained during 4th Wednesday of summer quarter. The minimum value of the output energy is 99.008 KWh which is attained during 13th Wednesday of summer quarter.

The procedure described above is repeated for the autumn quarter, and the results are given below. Irradiation, voltage and current profile of mentioned PV system during sampling day hours of for autumn quarter are given in Fig. 8 (a) to (c).

Like the previous section, as depicted in Fig. 8 (a), irradiations on the PV arrays vary during times of the days. Maximum values of irradiation on the Wednesdays of autumn quarter vary between 477.66 to 874.67 watts per square meters. Maximum value, 874.67 watts per square meters, occurs on 1st Wednesday of autumn quarter. Minimum values of irradiation on the Wednesdays of autumn quarter vary between 1 to 2 watts per square meters. Here, minimum value, 1 watt per square meters, occurs on 13th Wednesday of autumn quarter.

Here, like the previous section, regarding the irradiation profile in the 13 weeks of the autumn quarter, as depicted in Fig. 8 (a), the output voltage of the PV arrays can be calculated as Fig. 8 (b). To have a comparison between two cases, the output power profiles of a PV system with only boost converter and PV system with boost converter and inverter are presented in Fig. 9.

To have a numerical comparison between two cases, like the previous section, the daily output energy of PV station with inverter and output energy of PV station with boost converter and inverter, during 13 Wednesdays of autumn quarter, have been calculated and mentioned in Table. 5. As in some cases, the PV arrays output voltage is below the cut-off voltage for initialization of the inverter, the output energy of PV station with the only inverter is zero. The maximum value of the output energy is 105.52 KWh which is attained during 6th Wednesday of autumn quarter. The minimum value of the output energy is 34.985 KWh which is attained during 11th Wednesday of autumn quarter.
The output power of a PV station located at Kabudrahang, Iran, 35°N and 48°E, varies in different days of a year according to the irradiation and weather conditions. As mentioned in the Fig. 3, for summer months, the available power from a PV station involving the only inverter is zero as the output voltage of PV panels is less than the cut-off value, 340 V DC determined by (6). The output power of PV station is increased in the case of applying a DC-DC boost converter before inverter as this procedure lengthen the harvesting time of solar beams energy from sunrise to sunset, except a few minutes after sunrise and before sunset.

Clear skies during months of autumn, without overcast, with medium ambient temperatures, help in achieving much energy from PV station.

Fig. 10 demonstrates the total harvested solar energy during specific days, Wednesdays, in the weeks of a year. As shown, the level of PV station energy production, when they are equipped with boost converter and inverter, is much more than the condition they are equipped with only an inverter.

As mentioned above, the output voltage of the PV arrays depends on the level of irradiation and temperature. Low voltage levels in the output of PV arrays cannot be applied to the inverter as they are below the cut-off voltage level. To produce power from PV arrays, separate boost converter and inverter sets with lower voltage ratings are needed. Here, another solution for the case of study is designed. The voltage of the boost converter is reduced from 480 V DC to 240 V DC, and the inverter voltage is reduced from 240 V AC to 120 V AC. This reduction in voltage levels results in achieving much more power in the output of PV station. Additional energy output in kWh on different days of the year when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC have been illustrated in Table. 6.

Following the illustrated results in Table. 6, Fig. 11 demonstrates the concluded graph of the captured energy difference in the case of applying two topologies when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC.

It can be concluded from Fig. 10 that the additional produced energy when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC in the PV system equipped only with inverter is much more in
comparison with the inverter equipped with boost converter and inverter. The converter with a boost converter facilitates a wide range of capturing solar energy for the PV station.

6. Conclusion

Output parameters of PV arrays, voltage-current-power, depend on irradiation and ambient temperature at the location of the PV station. Irradiation, directly, and temperature, inversely affect the captured energy from PV stations. In this paper, two topologies have been investigated on an 80 KW PV station located in Kabudrahang, Iran. The voltage of the boost converter and the inverter voltage have been considered 480 V DC and 240 V AC, accordingly. Two seasons, summer and autumn, have been considered for the simulations. Simulation results show that in the cases of low irradiation and high temperature, the decreased output voltage level of PV arrays may be below the cut-off voltage of the inverter. In these conditions, the inverter output voltage is zero, and no energy would be extracted. Simulation results show that maximum and minimum values of the extracted output energy are 228.2 KWh and 99.008 KWh during summer quarter. These values are reduced to 105.52 KWh and 334.985 KWh during autumn quarter, accordingly. As the output voltage reduces to the cut-off voltage of the inverter, during summer quarter no output energy is harvested in the case of applying an inverter in the output of PV arrays. Also, with different converter sets, the output power of the PV station changes accordingly. As the voltage of the boost converter is reduced from 480 V DC to 240 V DC, and the inverter voltage is reduced from 240 V AC to 120 V AC, much more energy would be captured.

Acknowledgment

The authors would like to thank Dr. Abir Chatterjee for his helpful advice on this paper.

References


**Figure caption**

Fig. 1. Single-diode model of PV module with series and parallel resistances.

Fig. 2. Topology of PV station connected to the grid: (a) Topology 1: PV arrays directly connected to the inverter (b) Topology 2: PV arrays is connected to the inverter through a boost converter

Fig. 3. Voltage, current, and power output of 80 kW PV station with and without boost converter as a function of irradiation and temperature: (a) PV voltage (b) PV current (c) PV output power without boost converter (d) PV power output with the boost converter.
Fig. 4. Irradiation received by an 80 kW generating station located at Kabudrahang, Iran for the weeks through a year.

Fig. 5. The environmental temperature profile of an 80 kW generating station located at Kabudrahang, Iran for the weeks through a year.

Fig. 6. (a) Irradiation, (b) voltage and (c) current profile of 80 KW PV station at Kabudrahang, Iran for the summer quarter.

Fig. 7. (a) Output power of PV station with an only inverter, (b) Output power of PV station with boost converter and inverter.

Fig. 8. (a) Irradiation, (b) voltage and (c) current profile of 80 KW PV station at Kabudrahang, Iran for autumn quarter.

Fig. 9. (a) Output power of PV station with an only inverter, (b) Output power of PV station with boost converter and inverter.

Fig. 10. Additional energy output from an 80 kW PV station in KWh in Kabudrahang, Iran on different days of the year when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC.

Fig. 11. Additional energy output from an 80 kW PV station in KWh in Kabudrahang on different days of the year when (a) the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC, (b) the inverter voltage is reduced from 240 V AC to 120 V AC.

**Table caption**

Table 1. Datasheet values and estimated parameters of a Mitsubishi module

Table 2. Parameters calculation of the 80 kW PV station

Table 3. Values of eccentricity correction factor of the earth’s orbit and declination angle for the Wednesdays of the under study

Table 4. The output energy of PV station during days of summer quarter applying two topologies; (a) with the only inverter, (b) with boost converter and inverter

Table 5. The output energy of PV station during days of autumn quarter applying two topologies; (a) with an only inverter, (b) with boost converter and inverter

Table 6. The energy output from an 80 kW PV station in KWh in Kabudrahang, Iran on different days of the year when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC.
Figures

Fig. 1. Single-diode model of PV module with series and parallel resistances

(a)

(b)
Fig. 2. Topology of PV station connected to the grid: (a) Topology 1: PV arrays directly connected to the inverter
(b) Topology 2: PV arrays is connected to the inverter through a boost converter
Fig. 3. Voltage, current, and power output of 80 kW PV station with and without boost converter as a function of irradiation and temperature: (a) PV voltage (b) PV current (c) PV output power without boost converter (d) PV power output with the boost converter
Fig. 4. Irradiation received by an 80 kW generating station located at Kabudrahang, Iran for the weeks through a year

Fig. 5. The environmental temperature profile of an 80 kW generating station located at Kabudrahang, Iran for the weeks through a year

(a)

(b)
Fig. 6. (a) Irradiation, (b) voltage and (c) current profile of 80 KW PV station at Kabudrahang, Iran for the summer quarter.
Fig. 7. (a) Output power of PV station with an only inverter, (b) Output power of PV station with boost converter and inverter.
Fig. 8. (a) Irradiation, (b) voltage and (c) current profile of 80 KW PV station at Kabudrahang, Iran for autumn quarter.
Fig. 9. (a) Output power of PV station with an only inverter, (b) Output power of PV station with boost converter and inverter

Fig. 10. Additional energy output from an 80 kW PV station in KWh in Kabudrahang, Iran on different days of the year when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC
Fig. 11. Additional energy output from an 80 kW PV station in KWh in Kabudrahang on different days of the year when (a) the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC, (b) the inverter voltage is reduced from 240 V AC to 120 V AC.

7. Tables

Table 1. Datasheet values and estimated parameters of a Mitsubishi module

<table>
<thead>
<tr>
<th>Datasheet parameters</th>
<th>Estimated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{SC}$</td>
<td>7.36 A</td>
</tr>
<tr>
<td>$V_{OC}$</td>
<td>30.4 V</td>
</tr>
<tr>
<td>$V_{mpp}$</td>
<td>24.2 V</td>
</tr>
<tr>
<td>$I_{mpp}$</td>
<td>50</td>
</tr>
<tr>
<td>$n_s$</td>
<td>50</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>7.36 A</td>
</tr>
<tr>
<td>$I_0$</td>
<td>0.104 μA</td>
</tr>
<tr>
<td>$A$</td>
<td>1.310</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.251 ohm</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>1168 ohm</td>
</tr>
<tr>
<td>$K_i$</td>
<td>0.057%</td>
</tr>
<tr>
<td>$K_v$</td>
<td>-0.346%</td>
</tr>
</tbody>
</table>
Table. 2. Parameters calculation of the 80 kW PV station

<table>
<thead>
<tr>
<th>Equivalent 80 KW PV arrays parameters</th>
<th>Relationship with module parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{ph}$</td>
<td>235.57 A</td>
</tr>
<tr>
<td>$I_0$</td>
<td>3.314 μA</td>
</tr>
<tr>
<td>$A$</td>
<td>1.310 A</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.117 ohm</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>547.77 ohm</td>
</tr>
</tbody>
</table>

Table. 3. Values of eccentricity correction factor of the earth’s orbit and declination angle for the Wednesdays of the under study

<table>
<thead>
<tr>
<th>Day</th>
<th>Jan5</th>
<th>Jan12</th>
<th>Jan19</th>
<th>Jan26</th>
<th>Feb2</th>
<th>Feb9</th>
<th>Feb16</th>
<th>Feb23</th>
<th>Mar2</th>
<th>Mar9</th>
<th>Mar16</th>
<th>Mar23</th>
<th>Mar30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_o$</td>
<td>1.033</td>
<td>1.032</td>
<td>1.031</td>
<td>1.030</td>
<td>1.028</td>
<td>1.025</td>
<td>1.023</td>
<td>1.019</td>
<td>1.016</td>
<td>1.013</td>
<td>1.009</td>
<td>1.005</td>
<td>1.001</td>
</tr>
<tr>
<td>$\delta$</td>
<td>-22.6</td>
<td>-21.7</td>
<td>-20.5</td>
<td>-19.0</td>
<td>-17.2</td>
<td>-15.2</td>
<td>-12.9</td>
<td>-10.5</td>
<td>-7.9</td>
<td>-5.2</td>
<td>-2.4</td>
<td>0.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Day</td>
<td>Apr6</td>
<td>Apr13</td>
<td>Apr20</td>
<td>Apr27</td>
<td>May4</td>
<td>May11</td>
<td>May18</td>
<td>May25</td>
<td>Jun1</td>
<td>Jun8</td>
<td>Jun15</td>
<td>Jun22</td>
<td>Jun29</td>
</tr>
<tr>
<td>$E_o$</td>
<td>0.997</td>
<td>0.993</td>
<td>0.989</td>
<td>0.985</td>
<td>0.982</td>
<td>0.979</td>
<td>0.976</td>
<td>0.973</td>
<td>0.971</td>
<td>0.969</td>
<td>0.968</td>
<td>0.967</td>
<td>0.966</td>
</tr>
<tr>
<td>$\delta$</td>
<td>6.0</td>
<td>8.6</td>
<td>11.2</td>
<td>13.6</td>
<td>15.8</td>
<td>17.7</td>
<td>19.5</td>
<td>20.9</td>
<td>22.0</td>
<td>22.8</td>
<td>23.3</td>
<td>23.4</td>
<td>23.2</td>
</tr>
<tr>
<td>$E_o$</td>
<td>0.966</td>
<td>0.967</td>
<td>0.968</td>
<td>0.969</td>
<td>0.971</td>
<td>0.974</td>
<td>0.976</td>
<td>0.979</td>
<td>0.983</td>
<td>0.986</td>
<td>0.990</td>
<td>0.994</td>
<td>0.998</td>
</tr>
<tr>
<td>$\delta$</td>
<td>22.7</td>
<td>21.8</td>
<td>20.8</td>
<td>19.1</td>
<td>17.3</td>
<td>15.3</td>
<td>13.1</td>
<td>10.7</td>
<td>8.1</td>
<td>5.4</td>
<td>2.6</td>
<td>-0.2</td>
<td>-3.0</td>
</tr>
<tr>
<td>$E_o$</td>
<td>1.002</td>
<td>1.006</td>
<td>1.010</td>
<td>1.014</td>
<td>1.017</td>
<td>1.020</td>
<td>1.023</td>
<td>1.026</td>
<td>1.028</td>
<td>1.030</td>
<td>1.031</td>
<td>1.032</td>
<td>1.033</td>
</tr>
<tr>
<td>$\delta$</td>
<td>-5.8</td>
<td>-8.5</td>
<td>-11.0</td>
<td>-13.4</td>
<td>-15.6</td>
<td>-17.6</td>
<td>-19.3</td>
<td>-20.8</td>
<td>-21.9</td>
<td>-22.8</td>
<td>-23.3</td>
<td>-23.4</td>
<td>-23.2</td>
</tr>
</tbody>
</table>

Table. 4. The output energy of PV station during days of summer quarter applying two topologies; (a) with the only inverter, (b) with boost converter and inverter

<table>
<thead>
<tr>
<th>Day</th>
<th>The output energy of PV station with an inverter (KWh/day)</th>
<th>The output energy of PV station with boost converter and inverter (KWh/day)</th>
<th>Max. value of output voltage (volt)</th>
<th>Day</th>
<th>The output energy of PV station with an inverter (KWh/day)</th>
<th>The output energy of PV station with boost converter and inverter (KWh/day)</th>
<th>Max. value of output voltage (volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>152.19</td>
<td>283.77</td>
<td>8</td>
<td>0</td>
<td>145.68</td>
<td>309.56</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>143.37</td>
<td>269.04</td>
<td>9</td>
<td>0</td>
<td>147.37</td>
<td>284.83</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>150.67</td>
<td>291.22</td>
<td>10</td>
<td>0</td>
<td>152.08</td>
<td>296.87</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>228.20</td>
<td>285.31</td>
<td>11</td>
<td>0</td>
<td>151.03</td>
<td>298.64</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>140.91</td>
<td>273.80</td>
<td>12</td>
<td>0</td>
<td>151.13</td>
<td>304.16</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>126.66</td>
<td>270.14</td>
<td>13</td>
<td>0</td>
<td>99.008</td>
<td>320.97</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>135.05</td>
<td>279.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table. 5. The output energy of PV station during days of autumn quarter applying two topologies; (a) with an only inverter, (b) with boost converter and inverter

<table>
<thead>
<tr>
<th>Day</th>
<th>Day</th>
<th>The output energy of PV station with an inverter (KWh/day)</th>
<th>The output energy of PV station with boost converter and inverter (KWh/day)</th>
<th>Max. value of output voltage (volt)</th>
<th>The output energy of PV station with an inverter (KWh/day)</th>
<th>The output energy of PV station with boost converter and inverter (KWh/day)</th>
<th>Max. value of output voltage (volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>74.021</td>
<td>327.65</td>
<td>89</td>
<td>66.368</td>
<td>66.368</td>
<td>413.06</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>92.111</td>
<td>330.23</td>
<td>85</td>
<td>45.140</td>
<td>45.140</td>
<td>397.87</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>47.450</td>
<td>324.88</td>
<td>91</td>
<td>47.025</td>
<td>47.025</td>
<td>401.00</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>48.611</td>
<td>349.34</td>
<td>97</td>
<td>34.985</td>
<td>34.985</td>
<td>417.92</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>28.852</td>
<td>349.90</td>
<td>103</td>
<td>85.670</td>
<td>85.670</td>
<td>433.94</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>105.52</td>
<td>398.44</td>
<td>112</td>
<td>63.972</td>
<td>63.972</td>
<td>430.20</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>62.793</td>
<td>391.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table. 6. The energy output from an 80 kW PV station in KWh in Kabudrahang, Iran on different days of the year when the voltage of the boost converter is reduced from 480 V DC to 240 V DC and the inverter voltage is reduced from 240 V AC to 120 V AC

<table>
<thead>
<tr>
<th>Day</th>
<th>Jan5</th>
<th>Jan12</th>
<th>Jan19</th>
<th>Jan26</th>
<th>Feb2</th>
<th>Feb9</th>
<th>Feb16</th>
<th>Feb23</th>
<th>Mar2</th>
<th>Mar9</th>
<th>Mar16</th>
<th>Mar23</th>
<th>Mar30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPPT with B &amp; I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>78.5</td>
<td>0</td>
<td>245</td>
<td>4.4</td>
<td>247.4</td>
<td>235</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>MPPT with I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Day</td>
<td>Apr6</td>
<td>Apr13</td>
<td>Apr20</td>
<td>Apr27</td>
<td>May4</td>
<td>May11</td>
<td>May18</td>
<td>May25</td>
<td>Jun1</td>
<td>Jun8</td>
<td>Jun15</td>
<td>Jun22</td>
<td>Jun29</td>
</tr>
<tr>
<td></td>
<td>539.6</td>
<td>79.8</td>
<td>78.5</td>
<td>545.2</td>
<td>165</td>
<td>253</td>
<td>236</td>
<td>153</td>
<td>161.5</td>
<td>157.7</td>
<td>145.9</td>
<td>159</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>MPPT with B &amp; I</td>
<td>0.14</td>
<td>0.16</td>
<td>0</td>
<td>0</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
<td>0.13</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>MPPT with I</td>
<td>152.2</td>
<td>143.4</td>
<td>150.7</td>
<td>228.2</td>
<td>141</td>
<td>126.8</td>
<td>135.2</td>
<td>145.8</td>
<td>147.4</td>
<td>152.1</td>
<td>151</td>
<td>151.1</td>
</tr>
<tr>
<td></td>
<td>74</td>
<td>92</td>
<td>47.5</td>
<td>47</td>
<td>25.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MPPT with B &amp; I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MPPT with I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Reza Kazemi Golkhandan received his BSc degree from Shahrood University of Technology in 2007, MSc degree from KN. Toosi University of Technology in 2010 and PhD degree from University of Birjand in 2018 in Iran. His main research interests include renewable energy systems, microgrids, frequency stability, power electronics and optimization methods.

Hossein Torkaman is currently an Associate Professor at the Faculty of Electrical Engineering, Shahid Beheshti University, Tehran, Iran. His main research interests include power electronics, electrical machines, and renewable energies.

Ali Keyhani received the B.E., M.S.E.E., and Ph.D. degrees from Purdue University, West Lafayette, IN, in 1967, 1973, and 1976, respectively. He is currently a Professor of electrical engineering at The Ohio State University (OSU), Columbus. He is also the Director of the OSU Electromechanical and Green Energy Systems Laboratory. Dr. Keyhani was the past Chairman of the Electric Machinery Committee of IEEE Power Engineering Society and the past Editor of the IEEE Transaction on Energy Conversion. He was the recipient of The Ohio State University College of Engineering Research Award in 1989, 1999, and 2003.